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Bachelor's Thesis in Maritime Navigation

Powering a Vessel in a Seaway

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Preface

This thesis was written during the summer of 2014, while conducting the literature review for the Master's Thesis in Naval Architecture and Ocean Engineering. The decision to write a theoretical thesis on powering a vessel in a seaway, stemmed from the interest of the author on the topic first and second to fulfill the academic requirements of the Bachelor's Degree in Maritime Navigation.

The entirely responsibility for any mistake or in adequateness that could remain in this thesis is the author's own.

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Barcelona, CATALONIA
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Abstract

The thesis "Powering a vessel in a seaway" is an introduction to methodology used by Naval Architects to predict the total hydrodynamic resistance of a vessel underway. The thesis starts breaking down the total resistance in its different components and having a look into each of its contributors. Since, one of the main contributors is the added resistance in waves, the thesis includes a chapter solely dedicated to this interesting phenomenon. Finally, the thesis ends with a chapter entirely dedicated on the methodology of predicting the added resistance.

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Colophon

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1.1 Background and Motivation

Nowadays an accurate prediction of the ship's resistance in waves had experience and increasing importance and interest from the designers, ship owners/operators and policy makers. The added resistance has a substantial effect on the engine/propulsion system selection and ship's performance in terms of sustain a service speed optimizing fuel consumption in a realistic seaway. Also, accurate predictions of the added resistance are necessary for the implementation of the modern on-board ship routing systems. The motivation to write this thesis stems from the wish of the author to consolidate his knowledge in hydromechanics in general and in seakeeping in particular getting deep into the added resistance in waves phenomena.

This chapter is a brief overview of the total resistance of a ship in a seaway and its component which include calm-water resistance; added resistance due to wind and a brief introduction on added resistance in waves plus added resistance due to steering and an the added resistance due to fouling. However, in case you are either familiar with the subject or no interested in it you can continue in chapter two(2) where the added resistance in waves is deeply discussed.

2.1 Powering a vessel in a seaway

A successful ship design eventually depends on two simple aspects: the vessels performance under way and her ability to sustain a defined speed. Therefore, the ultimate goal for a ship designer is to obtain the most accurate prediction for both of those concepts.

It could seem trivial, but nevertheless an accurate prediction of the ship motions, hydrodynamic resistance, propulsion requirements, and structural loads of a vessel in a realistic seaway is quite an intricate problem. This difficulty, however, it is being historically solved by Naval Architects with a simple approximation. The designers have been selecting the hull forms and ship's dimensions on the basis of the calm-water performance with insufficient regard on the sea and weather conditions that the vessel would face in her life span. Moreover, ship operators have had the very same approximation to this issue, operating or even acquiring vessels regardless of the sea and weather conditions.

This established system for estimating a vessel's propulsion requirement to sustain a certain speed under the environmental conditions namely wind and waves was usually based on adding an allowance or margin. This margin, also known as weather margin, was either based on the previous experience of the ship's operator or other similar vessels on the same routes or most occasions just by guessing. (P.A.Wilson)¹. In fact, this margin is a simple addition to the calm-water power requirement around 15 to 30 percent. For example, the weather margin for a ship operating solely in the Mediterranean Sea might be 10 percent, whilst to maintain a speed trans-Atlantic westbound, a ship might need a weather margin of 30 percent or higher. (A.F.Molland et al., 2011)²

Nowadays, this fair but neither efficient nor accurate prediction of the vessel powering requirements had become a thing of the past. Due to several factors such as economical impact, environmental awareness and regulation requirements the prediction of the powering requirements in ships has matured and become one of the main concerns for designers and operators. Now aspects such as added resistance in waves is taken seriously in account when designing a vessel in order to reduce the operational cost associated with fuel consumption. Motion predictions are in great interest when designing vessels with special requirements such as passenger vessels or offshore work-boats.

Therefore, the necessity of maintaining the service speed interacts between other design parameters, namely, calm-water resistance, power and ship motions within an accurate prediction. This concern for the speed and the performance under different sea conditions is paramount in the case of High-speed craft for the first and for Offshore vessels for the last.

Traditionally, as explained above, the approach of the designer was to solve this uncertainty by introducing an on-experience-based gain or allowance in power on top of the calm-water resistance in order to overcome the added resistance. Fortunately

¹(P.A.Wilson)

²(A.F.Molland et al., 2011)

with the progress made in seakeeping, in both analytic methods and experimental techniques, plus the access to cheaper computational power, now it is possible to determine the added resistance in a seaway with sufficient accuracy for designing purposes.

The added resistance is often represented as a increase of power or thrust increase to sustain a certain speed condition or a speed reduction with a fixed amount of available power as used in calm-water condition. A clear illustration of that is the following figure that shows in an intuitive way the representation of both phenomena. As it can be seen the red line is the power requirement at calm-water conditions and the blue line is the required power in natural sea state.

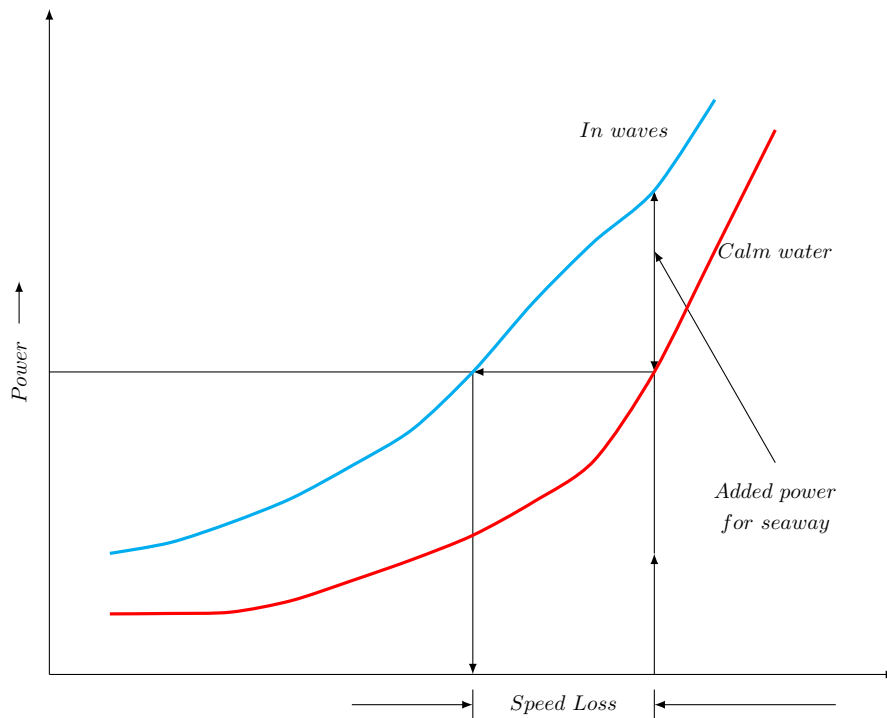


FIGURE 2.1: Speed loss or added power in a seaway

There are two main factors that reduces the speed of a vessel in a natural seaway. One is a voluntary speed reduction by captain indirectly induced by the sea condition. The other is the involuntary speed loss which the captains have no control over it and it is directly affected by the sea conditions.

- Voluntary Speed Loss
- Involuntary Speed Loss

The voluntary reduction can be attributed to action of captains to reduce the speed in order to decrease the violent motions of the vessel, among other causes the following:

- Shipping of excessive green water.
- Slamming.
- Excessive range of motions and accelerations that could shift the cargo.
- Excessive motions and impacts that could jeopardize the integrity of the vessel.
- Propeller racing.
- Difficulty in keeping course.
- Excessive motions, mainly heaving, pitching, that could reduce the comfort of the people on-board and the work-ability in transit.

In the other hand, the components of the involuntary ship speed loss of a vessel in a natural seaway are the following:

- Added Resistance cause by windage on the superstructure, hull and the auxiliary propulsion device.
- Added Resistance due to the ship motion, in terms of the rigid body modes. Greatly influenced by the Heave and Pitch motions. Also known as Radiation.
- Added Resistance due to wave reflection or diffraction of the wave system on the hull influenced by the hull geometry, water-plane surface and Block coefficient(C_b).
- Increase in resistance due to yawing and swaying motions, drift angle caused by wind and waves as well as rudder operation (movement).
- Loss in the efficiency of the propulsion system caused by operating in a fluctuating flow due to the motion fo the ship. This has an additional effect on the engine performance which does not allow the propeller to absorb all the engine power in a variable load condition. So,those could include the following:
 - Increase on resistance causing overloading of the propeller.

- Reduction in speed hence variation of the intake velocity at the propeller disk.
- Motions causing the variation of the inflow conditions (intake velocity and flow direction) at the propeller disk.
- Immersion and Emersion of the propeller causing variation on pressure conditions and/or air suction.
- Variation of other conditions affecting the main characteristics of the propulsive machinery.

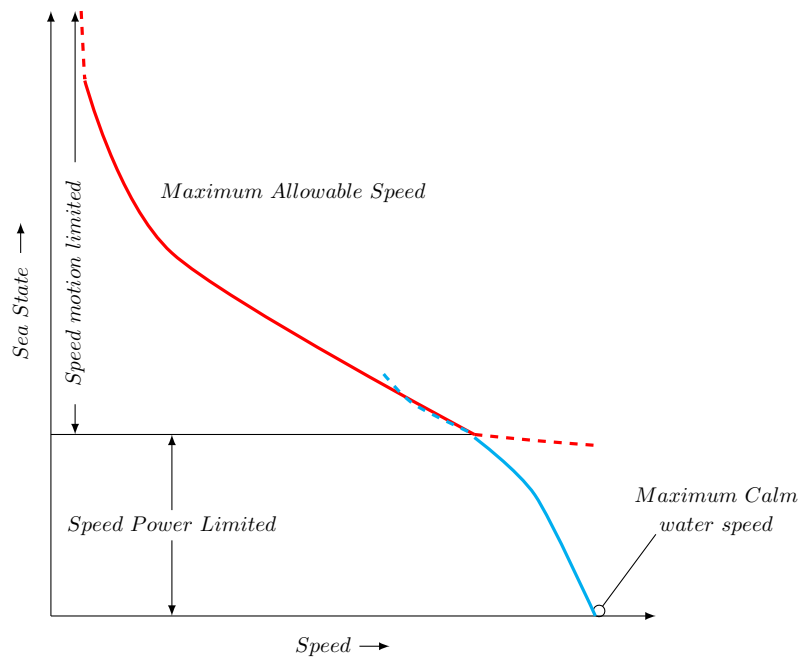


FIGURE 2.2: Voluntary and involuntary speed reduction

The figure above represents the regions of voluntary and involuntary speed loss in a head sea as function of sea state. It can be extracted from the figure that the ship's speed is power limited below a certain sea state, whereas above that sea state speed capability is motion limited. In general severe motions can be reduced only by a significant power reduction (e.g. voluntary speed loss) and added resistance is not important in such cases.

As it would be explained more in detail in chapter two (2) the added resistance can be predicted from model experiment, analytically and more recently through empirical methods. For instance in the case of model experiments models are towed either in regular or irregular waves, and the difference between the time-average resistance in waves and the resistance in calm water at the same speed is the mean added

resistance in waves. The most common model test are with models towed on head waves conditions since this one is the most critical or worst case scenario, where the vessel experience the maximum values of added resistance. Even though it limits its practical application. (P.A.Wilson)³ The results of analytical methods, which are based on known ship motions, tend to not completely agree with the experimental data, however the method provides adequate guidelines for the designer in estimating the power requirements in a seaway.

³P.A.Wilson

2.2 Overview on Calm-Water Resistance

The added resistance, also known as added resistance in waves, as mentioned before is an important aspect of a ship's design. To start acquiring the enough knowledge to proceed with the thesis, we will require to go through it. So, let's start refreshing some hydrodynamics principles.

Generally, in the mission or design specification, the required speed is without a doubt the most important design parameter of the propulsion system. This propulsion system has to overcome a certain hydrodynamic resistance at that specific speed, this resistance is also called Total Hydrodynamic Resistance, or more shortly total resistance. Which is quite a non-intuitive concept when trying to break its components down. The observation of a ship proceeding through water leads to notice two features: a wave pattern and a turbulent flow. As shown in the next figure, the first, is moving with the hull and the last is building up along the length of the hull and extending as a wake behind the hull. Both of these features of the flow absorb energy from the hull and so constituting, per se, a resistance force on it. This resistance force is transmitted to the hull as a distribution of pressure and shear forces over the hull; the shear stress arises as a consequence of the viscous property of the water. (A.F.Molland et al., 2011)⁴

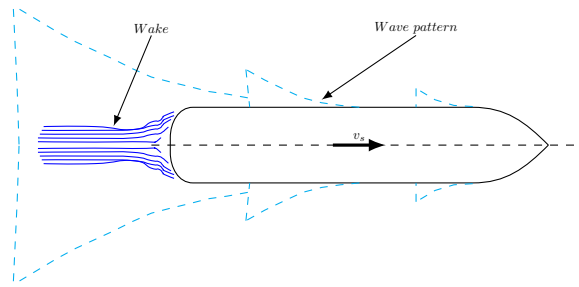


FIGURE 2.3: waves pattern and wake

This points towards one of the possible physical analysis of the resistance, the one considering the force acting on the hull:

- The force acting itemization:

Frictional Resistance: The fore and aft portions of the tangential shear forces τ acting over the surface of each element of the hull, Figure 1.4, can be integrated over the hull producing a total shear resistance or frictional resistance.

Pressure Resistance: The fore and aft portions of the pressure force P acting on each element of the hull, Figure 1.4, can be integrated over the hull in order to obtain a total pressure resistance.

⁴(A.F.Molland et al., 2011)

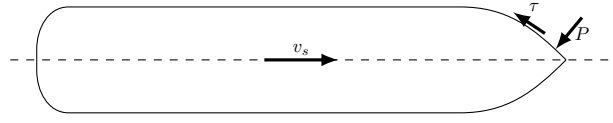


FIGURE 2.4: Frictional and Pressure Forces

The frictional drag emanate entirely due to the viscosity, however, the pressure drag is due partially to viscous effects and partially to hull wave-making effects.

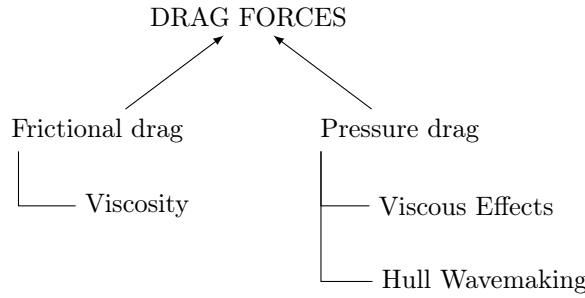


FIGURE 2.5: Components of Force Analysis

An other possible and perhaps more intuitive analysis is the one that considers the energy dissipation.

- The energy dissipation itemization:

Total Viscous Resistance: From the Bernouilli's theorem, $H = \frac{P}{\rho} + \frac{v^2}{2g} + h$ we can conclude that in the absence of viscous forces H (total Head or total Energy) is constant through the flow. That enable us to measure the local total head by means of a Pitôt tube. Since losses in total head are due to viscous force, it is possible to measure the total viscous resistance by measuring the total Head or Energy loss in the wake behind the hull as shown in the next figure.

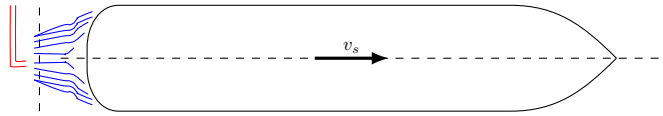


FIGURE 2.6: Measurement of Total Viscous Resistance

This viscous resistance is composed by the skin frictional resistance and a portion of the pressure resistance force. The total Head loss in the flow along the hull due to viscous forces results in a pressure loss over the aft-part of the hull that

culminates with a resistance due to pressure forces.

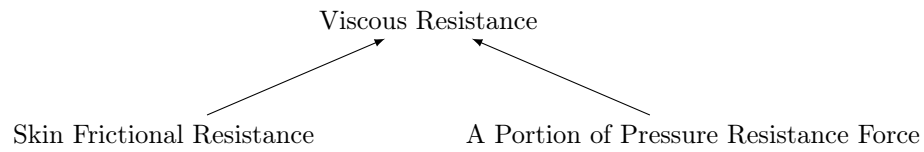


FIGURE 2.7: Components of Viscous Resistance

Total Wave Resistance: Since a hull proceeding through water creates a wave pattern. That pattern can be measured and broken down into component waves. The total wave resistant component can be obtained by estimating the energy required to sustain each wave component.

Consequently, it is possible to identify the following analysis of the hull total resistance by physical measurements:

- Pressure Resistance + Frictional Resistance
- Viscous Resistance + Remainder
- Wave Resistance + Remainder

These three can be combined to give a final breakdown as show in the following figure on components of hull resistance. It should be noted that each of the resistance components obeys a different set of scaling laws and the problem of scaling is made more complex because of interaction between these components.

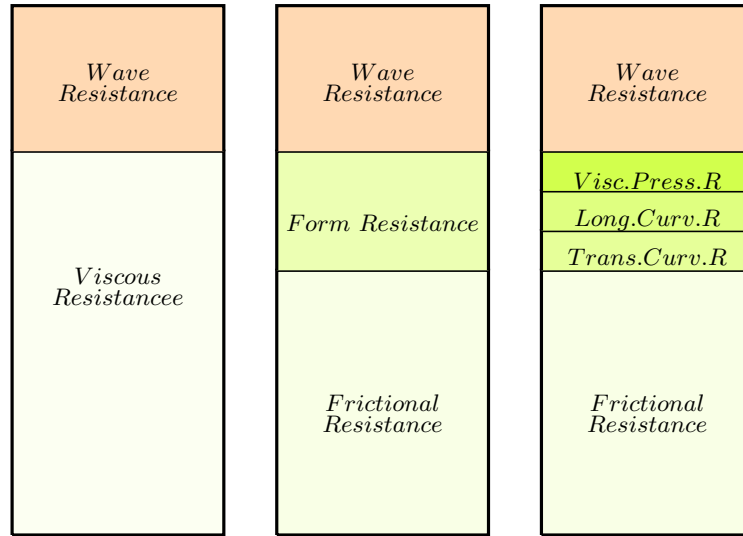


FIGURE 2.8: Components of Hull Resistance

The first column on the left illustrate the energy dissipation breakdown where the total resistance is made up of the sum of the energy dissipated in the wake and the energy used in the creation of waves, as we saw at figure 1.1 (wave pattern and wake). The other two columns show the force acting breakdown, however the column on the right is developed in more detail.

- Frictional or viscous resistance is the force that is the resultant of tangential forces acting on the hull as a result of the boundary layer along the hull.
- Form or Pressure Resistance is the Force that is the resultant of the normal Force on the hull, due to the difference in the pressure in front of and behind the moving ship. The pressure losses become significant when the boundary layer separates from the hull at the stern of the ship.

- Wave Resistance is the drag that is the result of wave generated by the moving ship. The kinetic and potential energy in the waves has to be generated by the propulsion system.

Often air resistance of the part of the ship above sea level cannot be neglected. The sum of frictional form resistance and wave resistance results in the total hull Resistance of the ship. It is often acceptable to assume that the ship's resistance is roughly proportional to the square of ship speed v_s for relatively low speeds.

$$R_t \propto v_s^2|_{\text{low speed}} \quad (2.1)$$

2.3 Added Resistance due to wind

A portion of the resistance of a vessel in calm-water conditions is due to the aerodynamic drag of the superstructure and the above water part of the hull.

$$F_{D_C} = C_D \frac{1}{2} \rho_A U^2 A_s \quad (2.2)$$

where:

F_{D_C} is the drag force in kN

ρ_A is the density of air ton/m^3

U is the speed of the ship in m/s

A_s is the maximum cross section area of the superstructure and above water part of the hull in m^2 The C_D or drag coefficient is determined from wind tunnel tests on a model of the super structure and the above water hull of the vessel. Because head waves come along with head winds and that fact increases the aerodynamic drag to:

$$F_{DA} = C_D \frac{1}{2} \rho_A (U + U_A)^2 A_s \text{ kN} \quad (2.3)$$

and the additional drag caused by the ambient wind U_A is:

$$F_{DA_{aw}} = C_D \frac{1}{2} \rho_A (U_A^2 + 2UU_A) A_s \text{ kN} \quad (2.4)$$

The contribution from wind is quite small compared with the increase in resistance do to waves. (Seakeeping)⁵ Although, we are not going deep into this subject, we want to mention that in 1973 Isherwood published a reliable method for estimating the wind resistance. That method is based on an analysis of the results of several wind resistance experiments carried out at different laboratories on a wide range of merchant ships. (Journee and W.W.Massie, 2001)⁶

⁵(Seakeeping)

⁶(Journee and W.W.Massie, 2001)

2.4 Added Resistance due to waves

The Added Resistance due to waves is the biggest contributor of the Added Resistance in a Seaway. Briefly, since the following chapter is going to get deep into this subject, we introduce the added resistance in waves as a steady force of second-order with respect to the incident wave's amplitude and acting opposite to the ship's forward speed in longitudinal direction. So when a ship has zero forward speed, then the added resistance is trivially identical to the longitudinal drift force. (Shukui Liu, 2011)⁷

⁷(Shukui Liu, 2011)

2.5 Added Resistance due to steering

When a ship is in a seaway her heading is disturbed by the wind and waves. In order to maintain a heading as steady as possible it is necessary to operate the rudder. The rudder angle counteracts the wind moment at any instant, however in the case of beam wind the effects are greater. This rudder operation increases the ship's resistance. In a wave field, because of the sea and the autopilot heading corrections, the vessel is going to experience yawing motions. These yawing motions induce centrifugal forces, which the component in the longitudinal direction increases, as show in the figure below, the vessel resistance.

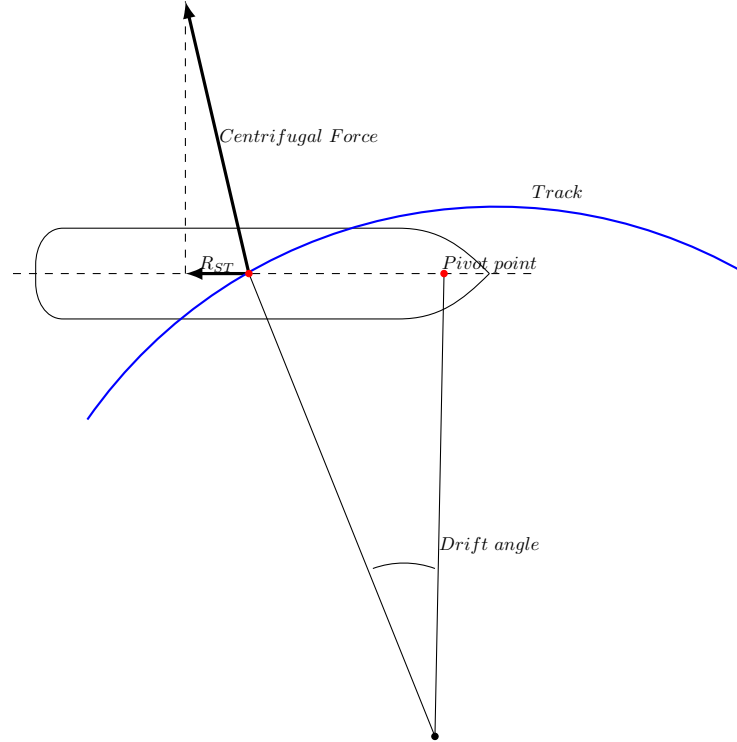


FIGURE 2.9: Added Resistance due to steering

The mechanism of the added resistance due to steering can be understood if for instance we assume a fixed position of the pivot point at 10% from the forward perpendicular and an added mass of 80% of the ship's mass. The order of the mean added resistance during a harmonic yaw motion is the following:

$$\overline{R_{ST}} \approx 0.0312 \nabla L \dot{\psi}_a^2 \text{ kN} \quad (2.5)$$

where :

∇ = volume of displacement in m^3 L = length of the ship in m

$\dot{\psi}_a$ = rate of turn amplitude in deg/min.

2.6 Added Resistance due to fouling

The fouling is indeed a biological process such as the growth of weeds and barnacles. This fouling of the hull creates an additional "roughness" and causes an increase on resistance of the vessel. Fouling will only effect the frictional part of the ship's resistance, R_F . (Journey and W.W.Massie, 2001)⁸ The total increase in "roughness" (including fouling) leads typically to an increase in C_F of about 2%-4% C_F /month. (?)⁹ If $C_F \approx 60\% C_T$, increases in $C_T \approx 1\% \sim 2\%$ /month.

The overall effect of Fouling on the total resistance is greater on low speed vessel with full forms due to the fact that the frictional resistance is the major contributor to the total resistance. Compared with high speed crafts where the wave-making resistance is in excess of the frictional part.

We are not going to extend this section however, to conclude we have to mention that fouling growth rates depend on environmental (fresh and coastal waters) and operational conditions (trade patterns). It is recommended to apply the adequate anti-fouling treatment on the hull and perform optimize the docking periods to avoid unnecessary fuel costs caused by an excess of fouling.

⁸(Journey and W.W.Massie, 2001)

⁹A.F.Molland

The Added Resistance is an important aspect of a ship's design and it is genuinely related to her seaworthiness - the ability of a ship to remain at sea in all conditions and to carry her specified duty - hence it becomes essential for the reader to acquire a strong knowledge of its idiosyncrasy, peculiarities and characteristics. This chapter pretends to yield the insight of Added Resistance in Waves in a such educational manner that the chapter is going to start with the main basic concepts and will progress to more complex aspects of the Second Order Drift Forces.

3.1 Added Resistance in Waves - Theoretical Background

In energy terms, the added resistance in waves is an extra-induced energy loss. What occurs is that when a ship is moving forward in a wave field generates two sort of waves: waves associated with the forward speed in calm-water, as we saw in the previous chapter, and waves associated with the motions caused by the incoming sea. Both kind of waves dissipate energy. In other words to generate those wave it is required a certain amount of energy. Hence, it is easy to figure out that if the vessel is sailing in ideal calm water condition, the second kind of waves -the ones associated with the wave field- are not going to be generated. Therefore, to maintain a forward steady speed, less energy is going to be required in contrast of sailing in the wave field condition.

This dissipated energy of a ship -in the form of waves-, according to the classical seakeeping theories, can be attributed to three(3) different components. All them are related to the energy supplied by the ship to the water and generated by the on-board propulsion plant.

Components of added resistance in waves:

- Added Resistance due to **Vertical Motions:**

This component is due to the interference between waves resulting from the ship motions (radiated waves) in particular heave and pitch and the incident wave system (diffracted waves when encountering the ship hull). This component is sometimes known as **drift force** and is the largest contributor to the added resistance in a long wave field.

- Added Resistance due to **Reflection:**

The incident waves are also reflected on the ship hull, and also interact with the ship radiated waves. This component is also known as **diffraction effect**. In a short wave field this component is the most significant however is the least contributor in other scenarios.

- Added Resistance due to **Viscous Effects:**

The "viscous" effect due to the **damping forces** associated with the forced heaving and pitching in calm water.

Those three(3) components involve energy dissipation. A major part of this energy is transmitted to the wave radiating from the hull and a very small part of energy is lost due to viscous friction. The energy consumed by those viscous friction is very small and negligible since viscous damping is insignificant compared to hydrodynamic damping of ship motions. (Arriba)¹ Therefore, the Added resistance in waves can be considered a non-viscous phenomenon, which is produced by potential effects (inertia and wave phenomena). This concept is a very important in practice when scaling from model experiments to full scale, allowing to obtain a full scale prediction of the

¹(Arriba)

Added resistance by multiplying the added resistance from the model by the cube of the scale ratio.

$$\frac{RAW_{ship}}{RAW_{model}} = \alpha^3 \quad (3.1)$$

Although it depends on the hull's form, in general it is considered that among the three(3) components of the added resistance, the **drift force** has the largest contribution followed by the **damping forces** and finally, with a very low contribution the **diffraction effect** that becomes the least significant of the three(3). (Jorgen Strom-Tejsen, 1973) ²

The next figure shows the relative magnitude of the two main contributors to the added resistance mentioned above: the ship motions (radiated effects) and the wave reflection (diffraction effects).

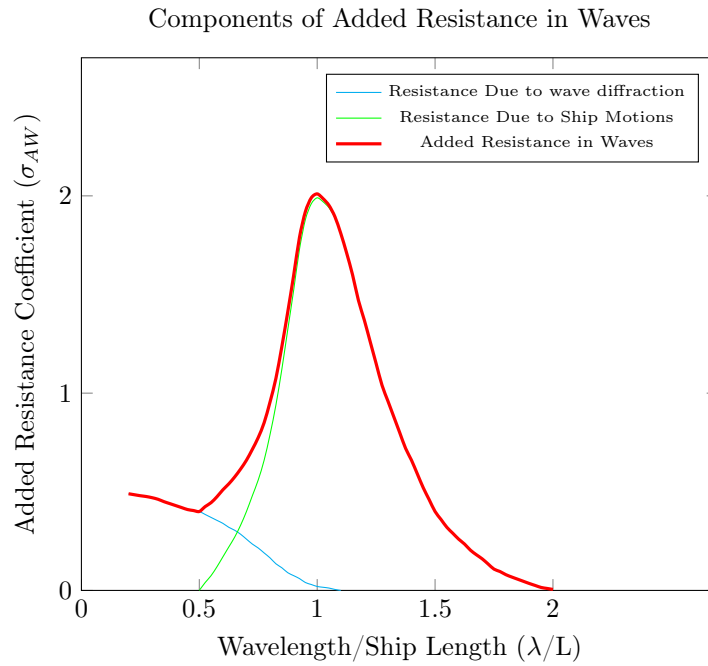


FIGURE 3.1: Components of Added Resistance

It is important to consider the fact that all three(3) components above are:

- Additive and able to be super-positioned.
- Proportional to the square of the wave amplitude and hence non-linear.

²(Jorgen Strom-Tejsen, 1973)

It is very interesting in order to understand the added resistance phenomenon to be able to separate those components above, however, because in reality all three components interact and are intrinsically related. It is not trivial to breakdown the three(3) parts. Fortunately, in practice it is possible to determine the force components individually by analytical methods or by special experimental techniques.

Since two of those contributors causes the majority of the added resistance in waves. We will explain those contributors next.

3.1.1 Motion Induced Added Resistance

The motion induced added resistance is originated from the radiated waves due to the ship motions. The wave radiation becomes larger when the relative wave elevation is larger, in particular when the relative wave elevation is larger than the incoming wave. The largest contributions to the relative wave elevation are heave, pitch motions and their phasing with the incoming or encountering wave. The roll motion of the vessel also contributes to that component, however the roll influence is, compared to pitch and heave components, very small, hence neglected. Things get interesting when the length of the wave is close to the length of the vessel. Here the pitch and therefore the relative wave elevation and added resistance are larger. That is the reason why the ratio between the ship length and the wave length (L_{pp}/λ) is such an important parameter in the phenomenon of the added resistance. When $L_{pp}/\lambda < 1$ (long waves relative to the ship length) the ship is moving with the waves and the relative wave elevation goes to zero(0) thus making the wave radiation and hence the added resistance go to zero(0) as well. Experience suggest that in cases where $L_{pp}/\lambda < 0.5$ the motion induced added resistance is virtually zero(0). Also, the motion induced added resistance goes to zero(0) in short waves (large L_{pp}/λ) where there are no ship motions and the relative wave elevation is in the order of the incoming wave. (Grin)³

3.1.2 Reflection Induced Added Resistance

In a short waves scenario ($L_{pp}/\lambda > 1$), the added resistance originates from the reflection of the waves against the hull. When the wave length (λ) is long compared to the ship length (L_{pp}) hence, a small (L_{pp}/λ) ratio, the wave reflection tends to zero. It could be seen as the long waves are not "influenced" by the presence of the ship. As we mentioned, the wave reflection starts to contribute from (L_{pp}/λ) ratio about 1 and we can consider a full reflection against the ship when this ratio becomes larger.

3.1.2.1 Wave Reflection and Diffraction

As very well explained by Journée and Massie in Offshore Hydromechanics by TU Delft, when a regular wave component encounters a vertical wall perpendicular to its direction of propagation, e.g. the side of a big ship, it is reflected and returned back to its origin with an equal (ideally) amplitude and velocity. The water surface near the ship side seems to move upwards and downwards with twice the amplitude of the incoming wave, describing a stationary wave - a wave without apparent any velocity component. This stationary wave or also known as **standing wave**, can be formulated by adding up two identical waves moving in opposite directions as follow:

The **standing wave** ζ equals, to add two identical waves ζ_1 and ζ_2 . Since the two wave profiles - the form of the water surface - are equal but they move in opposite directions. They would have the same amplitude ζ_a . A wave moving in the x-positive

³(Grin)

direction (expressed as function of x and t): $\zeta_1 = \zeta_a \cos(kx - wt)$ and a wave moving in the opposite direction (negative x -direction): $\zeta_2 = \zeta_a \cos(kx + wt)$

Then:

$$\zeta = \zeta_1 + \zeta_2 \quad (3.2)$$

putting it all together:

$$\zeta = \zeta_a \cos(kx - wt) + \zeta_a \cos(kx + wt) \quad (3.3)$$

when:

$$\cos(kx - wt) = \cos(kx) \cos(wt) + \sin(kx) \sin(wt) \quad (3.4)$$

$$\cos(kx + wt) = \cos(kx) \cos(wt) - \sin(kx) \sin(wt) \quad (3.5)$$

then:

$$\zeta = (\zeta_a \cos(kx)(\cos(wt) + \sin(kx) \sin(wt))) + (\zeta_a (\cos(kx + wt))) \quad (3.6)$$

$$\zeta = \cos(kx) \cos(wt) - \sin(kx) \sin(wt)) \quad (3.7)$$

$$\zeta = \cos(kx) \cos(wt) - \sin(kx) \sin(wt)) \quad (3.8)$$

$$\zeta = 2\zeta_a \cos(kx) \cos(wt) \quad (3.9)$$

The amplitude of this resulting wave is twice the amplitude of the two separated progressive wave components and the phase velocity becomes zero, as we can see in the next figure.

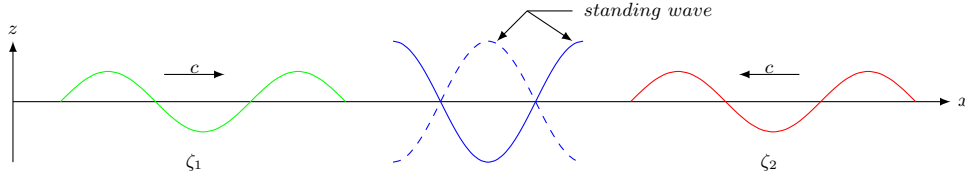


FIGURE 3.2: Standing Wave

In the case that the wave approaches the wall under a certain angle, the above approach continues to be valid for its component perpendicular to the wall. The wave is reflected away from the wall at an angle in the very same way as the light reflects from a flat mirror.

Waves and flow around the bow of a ship running in waves of short wavelength will result in considerable wave breaking phenomena showing high non-linearity. Many of the theoretical research on the resistance due to the diffraction on the hull do not consider the non-linear effect of the waves sufficiently to satisfy the boundary conditions of the free surface, so the calculations using such theories may not correctly explain the experimental results.

The following figure shows the influence of the bow shape and the diffraction phenomenon.

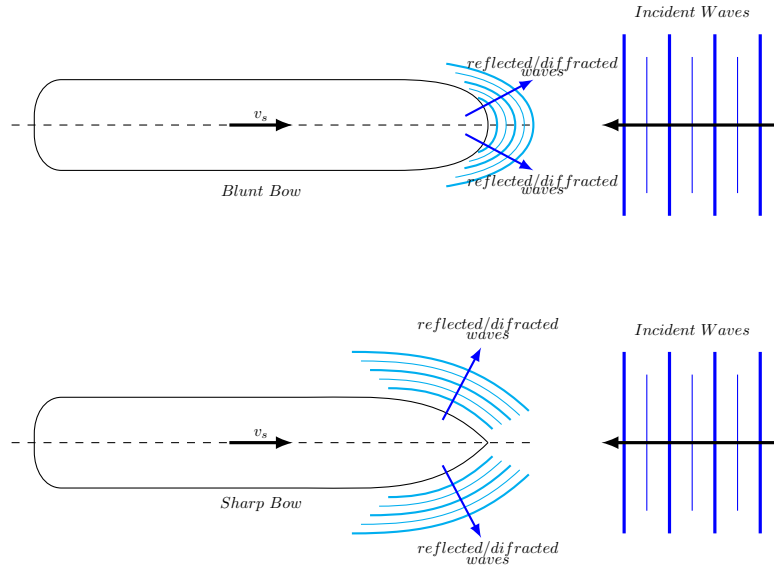


FIGURE 3.3: Blunt bow vs Sharp Bow

3.1.3 Added Resistance at Intermediate Wave Length

The two main contributors to the wave added resistance, the reflection induced and the motion induced added resistance appear combined in a relatively large wave length region. This region that can go from 1 to $2 L_{pp}/\lambda$ ratio. Next figure shows the model test results for a mid-size container vessel sailing in head regular waves.

In waves of short wavelength, the hull motion is small, and the resistance is mainly due to the diffraction of waves, and it is now as the wavelength increases, the added resistance due to the hull motion becomes dominant.

3.2 Motions, a First Order Response

It is being explained above that one of the most dominant components that induce added resistance are the vertical motions. That is why it is interesting to include this section. In order to model the motions and forces of a ship it is common to use a LTI system (Linear Time Invariant System). With the use of a LTI we consider the ship a system, where the input signal is a linear sine-wave that represents the incoming sea waves. And therefore, this systems delivers a response (output signal) in the form of a linear sine-wave that represents either a motion or a force. The LTI system is allowed to respond with a phase lag on the input signal and a linear change of the amplitude. Those restrictions give a very advantageous property of the LTI system in that the superposition principle can be applied.

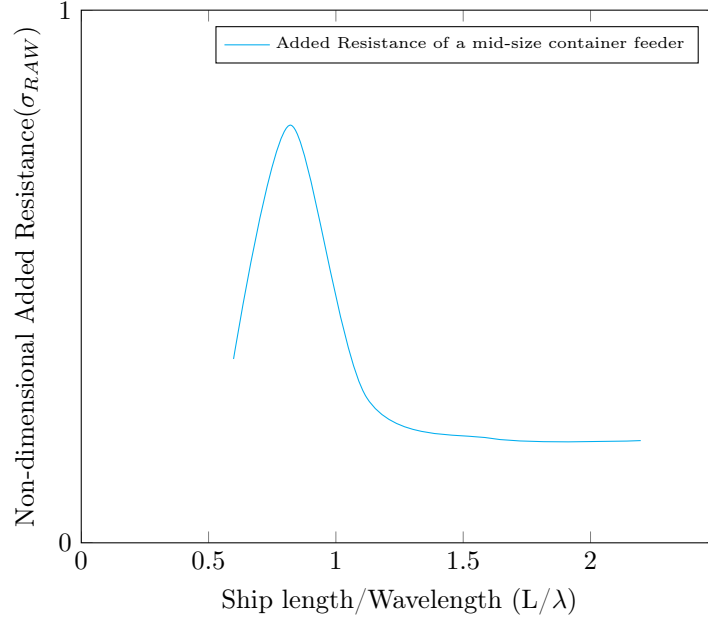


FIGURE 3.4: Non-dimensional Added Resistance with different different waves length regions

3.2.1 Superposition Principle

When a signal $x(t)$ can be expressed as the addition of sub-signals $x_k(t)$, with analogy the response to the signal $y(t)$ can be expressed as the sum of the response of the sub-signals $y_k(t)$.

$$x(t) = \sum_k x_k(t) \rightarrow y(t) = \sum_k y_k(t) \quad (3.10)$$

For that reason, ship motion and forces in irregular waves can be expressed as the sum of the responses in regular waves, making the linear time-invariant theory a powerful and useful for the analysis of the added resistance. However, in reality ships do not respond linearly to the incoming waves. In order to model the responses as a LTI system, the responses have to be linearized. But, because the linear part is dominating the response the ship motions are considered a first order problem. The application of the linear theory has the limitation of the waves steepness, when the waves steepness becomes too large, the non-linear effect becomes important and restrains its use.

3.3 Added Resistance, a Second Order Problem

The added resistance is the mean second order drift force in the opposite direction of the heading of the ship. Because the time mean value of an arbitrary sine wave, amplitude A and period T_e is zero(0), the mean force calculation using a linear force will result in a zero(0) mean value as follows:

$$\frac{1}{T_e} \int_0^{T_e} A \cos(\omega t + \epsilon) dt = 0 \quad (3.11)$$

In the case of a second order sine wave the result is a non-zero mean time value:

$$\frac{1}{T_e} \int_0^{T_e} (A \cos(\omega t + \epsilon))^2 dt = \frac{A^2}{2} \quad (3.12)$$

Hence, the quadratic term in the response has to be included in the problem, even though it is smaller compared to the linear term, to obtain a mean value. The added resistance in regular waves varies linearly with the wave height squared at a constant wave length, as we already mentioned. The added resistance then, is considered to be a second order problem. And this second order characteristic is the one that make it hard to obtain accurate predictions of the added resistance. This an issue that will be faced in this thesis. To give an idea on the limitations of the prediction of the added resistance, we have to take into account that if the ship motions are predicted with an accuracy of approximately 10~15%, the second order added resistance can not be expected to be of accuracy better than 20~30%. (Faltissen, 1990)⁴. The added resistance is very sensitive to motion prediction. Therefore, it is more important an accurate prediction of vertical motions than developing more sophisticated added resistance theories. (Arriba)⁵

Although added resistance is a second order problem, the linear wave velocity potential is the only one required. Higher order velocity potentials are not need to study the added Resistance. Faltissen (1990)

3.4 Added Resistance in Regular Waves

In the regular waves scenario, both the motion response and hence the added resistance are a theoretical "agreement". Since the regular waves scenario is not realistic because it only occurs in towing tank facilities and in mathematical modeling. However, with the principle of superposition already mentioned, we can consider that the responses of a ship to irregular waves can be considered as the summation of the responses to regular waves of all frequencies. And here is the importance of the analysis in regular waves since, first it is relatively simply and accurate to obtain the ship motion response and second, it eases the process to obtain the ship responses in an irregular sea state.

⁴(Faltissen, 1990)

⁵(Arriba)

3.5 Added Resistance in Irregular Waves

The validity of the application of the superposition to ship motion and sea loads is generally accepted. So, assuming that the principle of superposition is also valid for the horizontal responses, as we already explained. The complex problem of predicting ship motions and sea loads in a natural seaway can be reduced to the two problems:

- The motion and loads prediction in a regular sinusoidal waves.
- The statistical response prediction in an irregular sea using the regular waves result.

If the responses for a ship in regular waves are known, the procedures to follow is the one proposed by St.Denis and Pierson for determining the statistical response not only for a given sea state, but for a distribution of sea conditions which a ship may encounter in its life span (Abrahamsen, 1967). However, a major difficulty in seaworthiness analysis has been to make accurate predictions of motions and sea loads for a ship in regular waves. As we know this point If the designer knows the geometric description and the weight distribution and has adequate information about the sea environment, he can calculate the motions and the dynamics loads for a ship in a seaway with reasonable accuracy. It is possible to express the added resistance in irregular waves with superposition of the regular wave responses.

It is interesting to know, that even though the ship responses to regular waves do not indicate directly the behavior in irregular waves. If we combine a statistical treatment of the responses combined with the spectrum of the sea waves. We can obtain results which are significant for the ship motion in the realistic sea. We will develop more about this process in the following chapter, however we must mention that this technique of this process was first described by St.Denis and Pierson(1953) and it was applied to model test by E.V.Lewis(1955). Then Korvin-Kroukovsky(1956-1957) presented an explanation. In this process the square of the amplitude of ship motion per unit wave height, for a given wave length λ at a particular speed (i.e. for a given frequency of encounter), is multiplied by the ordinate of the sea spectrum (corrected to the ship speed) at the same frequency of encounter. In other words, for any encounter frequency, the ordinate of the response spectrum is obtained as the product of the ordinate of the encountering sea and the RAO(Response Amplitude Operator) for the same encountering frequency. Then, the mean added resistance in a irregular seaway is:

$$RAW = 2 \int_0^\infty S(w_e) \frac{R_{aw}(w_e)}{\zeta^2} dw_e \quad (3.13)$$

where:

$S(w_e)$ = Wave Spectrum

$\frac{R_{aw}(w_e)}{\zeta^2}$ = Added Resistance Response

dw_e = encounter frequency band

The wave spectrum is defined depending on the sea condition or it can be assumed for a given wind by using ITTC (International Towing Tank Conference) standard formation, which is a function of the significant wave height and of the modal period of the sea. In this thesis for instance the wave spectrum for the numerical simulation was selected from the model test wave conditions. Most of the time, the selected spectrum where JONSWAP (Joint North Sea Wave Project) and Betchsneider. Because of the scope of the thesis we are not going to extend the explanation on wave spectrum, so we suggest you, if you are interested, to review the extend literature about this matter.

3.6 The Mean Added Resistance

When a vessel is sailing in a wave field experience a fluctuating force in the opposite direction, and as we already know this is caused by the encountering waves. This fluctuating force is the total hydrodynamic resistance, however because there is a large variation of the resistance of the ship traveling in waves, increasing the resistance from the trough to the crest of the wave and decreasing the resistance from the crest to the trough. And also, due to cyclical phenomena nature. It is commonly to use, for design the understanding and design purposes, a more sensible measure, the average added resistance in a wave condition, also known as mean added resistance. The Mean Added Resistance is a steady force of second-order with respect to the incident wave's amplitude an acting apposite to ship's forward speed in longitudinal direction. In other words the Added Resistance is the longitudinal component of the mean second-order wave force.

So this total hydrodynamic resistance is composed by the calm water resistance and the added resistance. And in head seas the mean value of the total resistance will be greater than the calm water resistance and the difference may be attributed to the effects of the waves.

$$\begin{aligned} \text{Total Resistance} &= \text{Calm Water Resistance} \\ &+ \\ &\text{Added Resistance} \end{aligned}$$

The next figure shows that phenomenon where it can be distinguish the mean added resistance and the calm water resistance. That is why, it must be noted that the added resistance is independent from the calm water resistance.

This interesting phenomenon of the ship resistance increment due to waves can be studied from different approaches. The basic principles mentioned above may lead to a variety of formulations of the very same problem. Although it could seem that all those approaches to the added drag issue should encounter a similar, with the sake of their assumptions, solution. We will see that it is not the case and that some approaches are more accurate and reliable than others. This discrepancy is due to the different nature of the required input information and the inherent manipulation of

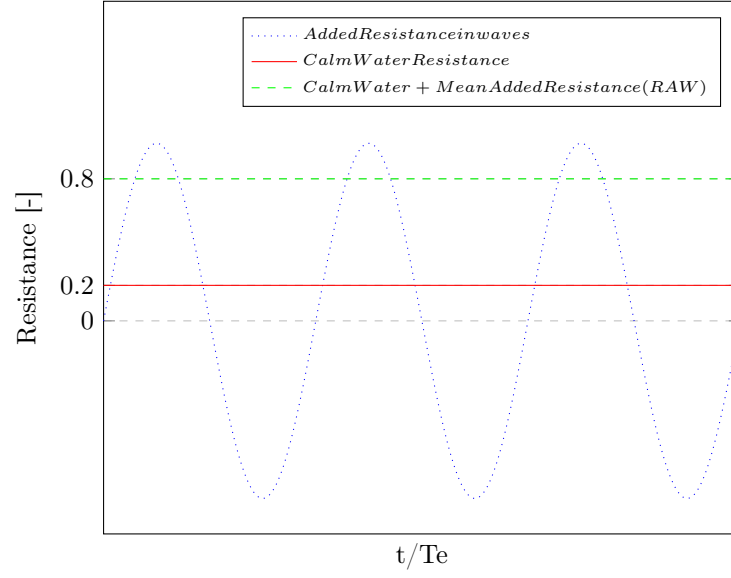


FIGURE 3.5: Components of Added Resistance in Waves

that data. Mention all the methods is possible, however, getting into detail it would be an extreme endeavor that would escape from the scope of the thesis. That is why we will just introduce the methods used for the computation of the added resistance in this thesis. And, in the following chapter, we will give a brief description and develop the methods considered more relevant.

Since the added resistance has an impact in a wide variety of aspects on a ship's performance in a seaway. Therefore the most accurate predictions of the added resistance is an important aspect of a vessel design. That range of aspects can go from safety in rough weather conditions to economical aspects(fuel consumption) in moderate weather conditions. Hence, those aspects are embedded in the operability study of a vessel's profile. This margin that is mostly due to added resistance in waves, can have severe consequences if it is not accurately estimated. If the margin is too low, the safety of passenger and cargo on-board can be in risk and the arrival time will be too low. Whenever this margin is too high, the engine will run most of the time in a non-efficient regime and in a future could not comply with new environmental regulations such as EEDI(Energy Efficiency Design Index) and jeopardizing the operability and life of the vessel.

In this chapter we will see that the added resistance in a seaway may be predicted by either analytically, numerically or by model experiments carried out both in regular and irregular waves. Predicting the Added Resistance of a ship in waves is equivalent to do a performance evaluation of the vessel in a certain seaway. To do those estimations several approaches had been done, such as using experimental fluid dynamics(EFD), Potential Flow Theory(PFT) and Computational Fluid Dynamics(CFD).

The second order nature of the added resistance and the fact that is based on mean value of wave force, makes its value relatively small compared to the excitation force. (?)¹ That makes things more complicated and the same time more interesting. When dealing with Added Resistance the accuracy required in both the experimentation and the calculations is paramount for the outcome of our prediction.

In this section we will discover the different methods to predict the Added Resistance and the theory behind.

¹(?)

4.1 Prediction Methods

The added resistance in waves phenomenon can be studied from several points of view. They can be generally classified into two main categories, namely far-field and near-field methods. The far-field methods are based on considerations of the diffracted and radiated wave energy and momentum flux at infinity, leading to the steady added resistance force by the total rate of momentum change. The near-field method, on the other side, leads to the added resistance as the steady second-order force obtained by direct integration of the hydrodynamic, steady second-order pressure acting on the wetted ship surface. The latter can be calculated exactly from first order potential functions, and their derivatives. The researchers are being focused on applying both linear and non-linear PFT (Potential Flow Theory). In the Linear potential flow case the added resistance force is estimated from velocity potential and fluid pressure solution corrected with the perturbation method to include the higher order terms. Using the Pressure Integration method (PIM) (Havelock,1942; Boese, 1970; Salvessen, 1978), the Momentum and Energy Method (Maruo, 1957 and 1963) and Radiated Energy Method (Gerritsma and Beukelman, 1972).

Those basic principles or theories can be applied in different formulations or methods for the same problem and sometimes the same method acquire different names making sometimes complicated for the reader to have a clear picture of the whole process. That is why we will try to ease the comprehension of the reader by making a clear differentiation between theories and methods.

In general the following are the three(3) general methods to predict the Added resistance in waves:

- Havelock Theory
- Momentum and Energy Methods
 - Lin and Reed
 - Maruo
- Radiated Energy Methods
 - Gerritsma and Beukelman
 - Loukakis and Sclavounos
 - Journee
- Integrated Pressure Methods
 - Maruo
 - Salvesen
 - Boese

In this section we will introduce first Havelock theory and then three formulations, Maruo and Joosen, then Gerritsma and Beukelman and finally Boese.

It is interesting to mention that Faltisen et al. 1980 published a method free of empirical corrections and based on a simplified physical model of diffraction against an infinitely long vertical cylinder, that only accounts for wave reflections. And is in contrast with previously mentioned methods, Faltisen's method just requires the shape of the waterline.

The developments in computational and experimental studies for wave loads and motions of a ship are categorized according to the domain of calculations (frequency domain or time domain), the type of singularities used (Green or Rankine sources), the dimensionality of the problem solved (2-D or 3-D) and the order of the problem solved (linear or higher order). (25th Committee)² It is also interesting to note that, the natural trend in the respective state-of-the-art is to move from the frequency domain to the time domain, from the strip-theory type to fully 3-D schemes, from linear to nonlinear problems, and also from potential-flow to viscous-flow computations. (25th Committee)³

4.1.1 Far-field Method

The **Far-field Methods** are based on considerations of the diffracted and radiated wave energy and momentum flux at infinity, leading to a steady added resistance force by the total rate of momentum change.

- Far-fiel method was first proposed by Maruo (1957).
- Joosen (1966), Newman (1967): Strip Theory Method.
- Gerritsma and Beukelman (1972), Salvesen (1978): Radiated Energy Method.
- Joncquez et al.(2008): Rankine Panel Method in Time Domain.
- Kashiwagi et al.(2009): Enhanced Unified Theory (EUT) + correction in short waves.

The first **Far-field Method** was introduced by Maruo(1957) in the late 50's and then it was further elaborated in the following years by also Maruo(1960,1963) and Joosen(1966). We will explain Marou's and Joosen's methods and for the latter we will have a extended explanation due to its interest and simplicity.

In the early 70's, the first **Near-field, Direct Pressure Integration methods** appeared. The considered hydrodynamic pressure distribution was highly simplified by using a linear strip theory (e.g. Boese, 1970). At about the same time, the radiated energy approach of Gerritsma and Beukelman (1972) was introduced, which is basically following the far-field approach of Maruo. Strom-Tejsen et al. (1973) does a thorough evaluation of all the above approaches to find large discrepancies between the numerical results form different theoretical approaches and relevant model experimental data.

²(25th Committee)

³(25th Committee)

Later on, Salvesen (1974) investigated the added resistance problem by applying Gerritsma and Beukelman's method, but using Salvesen-Tuck-Faltisen method (STF) seakeeping strip theory and found quite satisfactory results.

4.1.2 Near-field Method

The **Near-field Method** leads to the added resistance as the steady second-order force obtained by direct integration of the hydrodynamic, steady second-order pressure acting on the wetted ship surface. The latter can be calculated exactly from first-order potential functions, and their derivatives. The Near-field Method is sometimes also referred as Direct Pressure Integration Method or Hull Pressure Method (Wilson P.A.)

4.1.3 Havelock's Theory

T.H.Havelock in his paper "The drifting force on a ship among waves" in 1942 proposed a formula to compute the mean added resistance due to heave and pitch motion of a vessel, at any frequency of encounter in head seas. His work was based on integration of the longitudinal component of the pressure over the wet part of the ship's hull neglecting the disturbing effect of the ship's surface upon the wave motion. In other words Havelock computed the Froude-Krylov or Froude-Kriloff force (depending on the author) which is the force induced by the unsteady pressure field generated by undisturbed waves. Havelock was a pioneers in computing the added resistance in regular waves proposing an equation for the Added Resistance R_{AW} , expressed as a function of the heave amplitude z_a and pitch amplitude θ_a , as follow:

$$R_{aw} = -\frac{k}{2}(F_a z_a \sin \epsilon_{zF} + M_a \theta_a \sin \epsilon_{\theta M}) \quad (4.1)$$

where:

R_{aw} = Added Resistance in Waves

k = wave number

F_a = exciting force

M_a = exciting moment

z_a = heave amplitude

θ_a = pitch amplitude

ϵ_{zF} = phase angle between the exciting force and the heave amplitude

$\epsilon_{\theta M}$ = phase angle between the exciting moment and the pitch amplitude

Havelock avoided the difficult problem of evaluating the complicated diffracted waves by using the Froude-Krylov hypothesis, that is the reason that his proposal was consider just an approximation. Even though Havelock neglects diffraction effects and pitch-heave cross coupling, the theory still provides some valuable insights into added resistance.

It is interesting to note that the Froude-Krylov forces does, along with the diffraction force which is the force due to the floating body disturbing the waves, make up the total non-viscous force acting on a floating body in regular waves.

From the equation proposed by Havelock we can extract the following conclusions:

- Both the motion amplitudes and their phases are important factors when calculating the added resistance.
- The maximum added resistance will likely occur in the region of pitch and heave resonance.
- A vessel with poor motion characteristics will have less added resistance due to the direct pitch and heave motion relationship.

4.1.4 Momentum and Energy Method - Maruo and Joosen's Theories

This method also called **Drift force method** is mathematically based on first, considering a control volume surrounding the ship's hull and later derive an energy or momentum balance. The velocity potential is divided into three(3) components:

- the incoming wave field (incident waves)
- the diffraction of the wave system by the body (diffracted waves)
- the diffraction of the wave system due to oscillating body in a regular field (radiated waves)

The resultant boundary value problem can be solved and since the potential of an incident waves is known, the solution to the problem consist in finding the harmonic potential that satisfies:

- a linearized free surface condition
- ship hull boundary condition

Those conditions are simplified if considering the slender-body assumptions.

The two greatest contributors to this theory are first Maruo that was the pioneer in developing a method as we will explain next, and then Joosen that extended the work done by Maruo.

4.1.4.1 Maruo's Method or Potential Flow Solution

Maruo obtained a value for the diffraction and radiated potentials. The forces on the ship were calculated from the mentioned linear momentum flow through the control volume around the ship hull. It must be noted that this potential flow formulation is the most rigorous formulation among several alternatives approaches to the problem of calculating the added drag in waves. However, is not the most appealing from a physical point of view. This theory leaves an extensive space for theoretical refinements and extensions. (Jorgen Strom-Tejsen, 1973)⁴ In order to represent the hull form, Maruo uses a singularity distribution. Then, the wave field potential consists of the potential associated with the regular wave field and the velocity potential of the waves produced by the singularities. The velocity potential of the regular wave may be written immediately in a simple harmonic form. The hull form generating singularity distribution is a known quantity or may be determined from an approximate distribution such as the center plane source distribution originally employed by Maruo. Maruo has shown that the pitching and heaving motion of the ship dominates the effects of surge and, therefore, he has been able to justify neglecting the effects of variations in ship speed as it will be mentioned in the discussion of experimental techniques.

4.1.4.2 Joosen Theory or Drift force Approach

The foundation of Joosen's theory developed in 1966 was to consider a control volume around the ship and then derive an energy or momentum balance. As it is already said above, Joosen has the same approach as Maruo in his analysis of drifting force of a body in waves. In fact Joosen extends Maruo's expression into an asymptotic series with respect to the slenderness ratio L/B and kept the first order terms. Hence, leading to the Joosen's simple expression for the added resistance:

$$R_{aw} = \frac{w^3}{2g} (N_z z_a^2 + N_\theta \theta_a^2) \quad (4.2)$$

where:

N_z = damping coefficient of heave.

N_θ = damping coefficient of pitch.

z_a = heave amplitude

θ_a = pitch amplitude

g = gravity

⁴(Jorgen Strom-Tejsen, 1973)

This slender body approximation is only valid for short waves and produces a speed independent added resistance. The theory was extended by Joosen to account for forward speed by substituting the wave encounter frequency w_e for the wave frequency w in the equation above.

$$\sigma_{aw} = E_1 + E_2 + E_3 \quad (4.3)$$

where:

$$\begin{aligned} E_1 &= C_o B_{33} \left(\frac{z_a}{\zeta_a} \right)^2 \\ E_2 &= C_o \left(2\phi \frac{L}{\lambda} \right)^2 B_{55} \left(\frac{\pi_a}{k\zeta_a} \right)^2 \\ E_3 &= -2C_o \left(2\pi \frac{L}{\lambda} \right) B_{3,5} Z_a \theta_a \cos(\epsilon) \\ C_o &= \frac{1}{16} \frac{L^2}{B^2} \left(w_e \sqrt{\frac{L}{g}} \right)^3 \frac{\nabla}{L^3} \\ \epsilon &= |\epsilon_z - \epsilon_\theta| \end{aligned}$$

The damping coefficients appearing in the above equations are given by:

$$\begin{aligned} B_{33} &= \left(\frac{1}{w_e \nabla} \right) \left(\frac{g}{L} \right) \int_{x_o}^{x_f} \beta(\xi) d\xi \\ B_{3,5} &= \left(\frac{1}{w_e \nabla} \right) \left(\frac{g}{L} \right) \int_{x_o}^{x_f} \xi \beta(\xi) d\xi \\ B_{55} &= \left(\frac{1}{w_e \nabla} \right) \left(\frac{g}{L} \right) \int_{x_o}^{x_f} \xi^2 \beta(\xi) d\xi \end{aligned}$$

where:

$$\begin{aligned} \nabla &= \text{displacement of the body} \\ w_e &= \text{frequency of encounter} \\ \beta(\xi) &= \text{sectional damping coefficient} \end{aligned}$$

The integrals are evaluated along the length of the ship with ξ defined as $\xi = x/l$. The damping sectional damping coefficient $\beta(\xi)$ is evaluated for each section.

Joosen concluded that the drift force in the longitudinal direction in head seas depends only on the potential of the radiated waves, and that the wave diffraction effect may be neglected except for very small waves in which case it becomes dominant. In a regular wave case study, the Joosen's theory can be taken over other methods such as Gerritsma and Beukelman. Even though Joosen is not as accurate as Gerritsma and Beukelman, it is easier in terms of implementation.

4.1.5 Radiated Energy Approach/Method - Gerritsma and Beukelman Theory/Method

The Radiated Energy Method was first applied by Gerritsma and Beukelman, that is the reason why sometimes there is a bit of confusion on how to refer to this method.

From the Radiated Energy approach we can extract that the added resistance can be seen has the result of a damping waves radiated away from the ship's hull. Gerritsma and Beukelman saw in this method a way to compute the added resistance by calculating the energy flux radiated from the ship's hull. In other words, Gerritsma and Beukelman saw the direct relationship of the added resistance to the energy contained in the damping waves. They proposed that the energy radiated during on wave encounter period T_e will be given by:

$$E = \int_0^{T_e} \int_{x_o}^{x_f} b(x) V_z^2(x, t) dx dt \quad (4.4)$$

where:

$b(x)$ = damping coefficient of the body at any longitudinal position.

$V_z(x, t)$ = vertical velocity of the ship section relative to the disturbed water surface elevation.

The coordinate position is given as the distance froward of the longitudinal center of gravity of the ship (LoG), and x_o and x_f are the positions of the aft and fore perpendiculars, respectively. With the expression above, Gerritsma and Beukelman equated the energy radiated to the added work done by the ship during the same period. Since the relative velocity V_z is a harmonic function of time which can be express as:

$$V_z(x, t) = V_{zo} \cos(w_e t + \epsilon) \quad (4.5)$$

the time dependence can be integrated yielding

$$E = \frac{\pi}{w_e} \int_{x_o}^{x_f} b(x) V_{zo}^2 dx \quad (4.6)$$

Referring to the work by Hanaka et al. (1963), Gerritsma and Beukelman showed that the added resistance work of the ship is proportional to the radiated energy

$$E = (V + c) T_e R_{AW} = \lambda R_{AW} \quad (4.7)$$

where λ is the regular wave length. This yields to

$$R_{AW} = \frac{k}{2w_e} \int_{x_o}^{x_f} b(x) V_{zo}^2(x) dx \quad (4.8)$$

where V_{zo} is proportional to the wave height. This elegant and simple result requires an accurate knowledge of the distribution of the sectional added-mass and damping

coefficient $b(x)$ to obtain added resistance for various motion conditions. Expanding the equations of motions for heave and pitch (force and moment equations, respectively), Gerritsma and Beukelman (1967) have shown that the damping coefficient $b(x)$ is given by:

$$b(x) = N(x) - V \left[dm(x)/dx \right] \quad (4.9)$$

where:

$m(x)$ = zero-speed sectional added-mass

$N(x)$ = zero-speed sectional damping coefficient

V = ship's velocity

Since the derivative of the added-mass coefficient is not always well defined in numerical applications for the end points by the ship, the added resistance equation may be simplified by partial integration if the added-mass coefficient vanishes at the forward and aft perpendiculars. This yields directly

$$R_{AW} = \frac{k}{2w_e} \int_{x_o}^{x_f} \left[N(x)V_{z_a} + 2Vm(x)\frac{dV_{z_a}}{dx} \right] V_{z_a} dx \quad (4.10)$$

For the Froude-Krylov hypothesis - which assumes that the water pressure on the hull (and hence the wave field) is unaffected by the presence of the vessel - Gerritsma and Beukelman used a dynamic correction. This correction takes the form of a modification of the incident wave amplitude by the hull surface. For deep-water, this correction to the wave height ζ is:

$$\int_{z_k}^{z_{wl}} \frac{y(z)}{y(z_{wl})} e^{kz} dkz = 1 - \frac{\zeta^*}{\zeta}$$

where:

$y(z)$ = offset distance over the vertical coordinates z_k = bottom position z_{wl} = water-line

So, the correction considering the incident wave amplitude by the hull surface is:

$$\zeta^* = \zeta \left(1 - \frac{k}{y_w} \int_{z_k}^{z_{wl}} y_b e^{kz_b} dz_b \right) \quad (4.11)$$

where: y_w = the half-width of the waterline y_b and z_b = the offset of the hull
 ζ^* is the effective vertical water displacement for a cross section. ζ is the undisturbed wave height.

The vertical relative velocity V_{z_a} follows from displacement equation

$$\xi = z - x_b \theta - \zeta^*$$

$$V_{z_a}(x, t) = \dot{z} - x_b \dot{\theta} + V\theta - \dot{\zeta}^* \quad (4.12)$$

The radiated energy method gives the simplest description in quartering and beam seas. The major assumption inherent in head and following seas is transverse symmetry of all physical processes. Motion is limited to heave and pitch and there is no asymmetric modification of the wave field by the hull.

Gerritsma and Beukelman could be more accurate due to its more accurate handling of diffraction effects and cross coupling compared with Joosen's method. However, compared to Joosen's method the Gerritsma and Beukelman method is more complicated to implement since it requires an accurate knowledge of the distribution of the sectional added mass and damping while the Joosen's method requires only the final total damping coefficients of the hull, which are more readily available.

4.1.6 Integrated Pressure Method - Boese's Method

The IPM (*Integrated Pressure Method*) is a near-field method that computes the Added Resistance integrating the hydrodynamic pressure on the body surface. It uses Bernoulli's equation combined with Taylor's expansion of the pressure about the mean position of the ship. In other words, the IPM is a classical hydrodynamic solution that integrates the longitudinal components of the oscillating pressure on the wetted surface of the hull and Boese(1970) led in this approach. So, what Boese did is to study the added resistance in a similar way as Havelock deal with the problem. However, Boese introduced a more elaborated initial motion data consideration. And, is just there, in the method chosen to determine the pressure distribution on the hull where the difficulty of this method relays. Boese, to compute the pressure distribution, employed a linear strip theory since a three-dimensional pressure distribution on a ship hull in waves was not accurately predicted at his time. The pressure forces acting on a ship are divided by Boese into two(2) segments as follows. The fluctuating force caused by the wave field and the heaving and pitching motion consist first of the integral of the pressure forces over a fixed surface, i.e., integration of the static waterline. This limited integration is justified on the grounds that first-order effects dominate in motion responses. The second resistance component arises, according to Boese, from the correction that one must make for the error originating from the limited integration mentioned previously. The dynamic pressure is neglected and a linear pressure distribution is assumed to be effective over the surface which is only occasionally wetted, owing to the ship motions. Computing the time-average contribution following the approach of computing the hull pressure distribution to the longitudinal force completes the calculation of added drag. An additional contribution following the approach of computing the hull pressure distribution was recently outlined by Hoffman (1972). Hoffman proposed a more complete evaluation of the hydrodynamic pressures on the hull using a transverses section strip theory. In principle, this would allow detailed sectional shape evaluation and include the ship-wave interaction and ship motion coupling in the analysis. A possible criticism

that can be made of all applications of transverse strip theory to the added resistance problem is that neglecting the interaction effect between the strips as required by the strip theory formulation, may not be appropriate for the calculation of added drag. Transverse strip theory has been found yield very accurate predictions of ship motion. The forces involved in ship motion lie predominantly in the plane of the transverse section in contrast with the unsteady force components contribution to added drag that are predominately longitudinal. The use of a transverse strip may therefore result in a poor problem formulation, and it is possible that a completely different approach is required for added drag theory. (Jorgen Strom-Tejsen, 1973)⁵

When using strip theory we are disabled to obtain the longitudinal forces directly, since there is no longitudinal effects between strips, so a mean value f^* of this force has to be obtained. This mean value f^* for a section (strip) at x_b can be express as:

$$f^* = \frac{\rho g \zeta^2}{4} \left(-1 + \frac{z_x^2}{\zeta^2} + \frac{2s \cos(-kx_b \cos(\mu) - \epsilon_s)}{\zeta} \right) \quad (4.13)$$

where:

$$z_x = Z_a - x_b$$

The added resistance obtained through this value is:

$$R_{aw1} = -2 \int_{x_o}^{x_f} f^* \frac{dy_w}{dx_b} dx_b \quad (4.14)$$

then:

$$R_{aw1} = -\frac{\rho g \zeta^2}{2} \int_{x_o}^{x_f} \left(-1 + \frac{z_x^2}{\zeta^2} + \frac{2s \cos(-kx_b \cos(\mu) - \epsilon_s)}{\zeta} \right) \quad (4.15)$$

The contribution of the vertical motions is obtained using:

$$R_{aw2} = \frac{1}{2} \rho \nabla w_e^2 Z_a \Theta_a \cos(\epsilon_z - \epsilon_\theta). \quad (4.16)$$

So, the total added resistance with this method will be:

$$R_{aw} = R_{aw1} + R_{aw2} \quad (4.17)$$

⁵(Jorgen Strom-Tejsen, 1973)

4.2 Numerical Methods

Each of the methods above require information about the hull. This information is obtained from the sectional offsets or sectional geometric coefficients depending on the method. Hydrodynamic characteristics such as added mass and damping coefficients are also required for the stations that define the hull of a ship.

The advancements in computer technology have made possible the development of new classes of three-dimensional numerical tools for analyzing problems in Naval Architecture, such as the one we are dealing with, the ship wave resistance and motions. Early attempts to model ships in potential flow focused on variation of slender body and strip theory to study simplified body geometries and free surface conditions. As computing power increased, so did the development of three-dimensional methods. Of these, considerable attention has been received by boundary element or panel methods.

4.2.1 Strip Theory

Strip Methods are the standard tool in evaluating ship seakeeping. An essential part of each strip method is the computation of hydrodynamic masses, damping, and exciting forces for each strip. This computation was traditionally based on conformal mapping techniques such as Frank's, Lewis etc, where an analytical solution for a semicircle was transformed to a shape resembling a ship section. This technique is not capable of reproducing complex shapes as found in the fore-body of modern ship such as bulbous bows and aft-parts of vessels.

We are not going to develop the strip theory in this thesis, however we have to mention that the 2-D theory takes into account that variation of the flow in the cross-directional plane is much larger than variation in the longitudinal direction of the ship. The principle of strip theory involves dividing the submerged part of the craft into a finite number of strips. Hence, 2-D hydrodynamic coefficients for added mass can be computed for each strip and then summed over the length of the body to yield the 3-D coefficients.

In strip theory we must consider the following:

Slender body theory, so in practice (roughly): $L/B > 3$.

The ship's cross sections don't produce longitudinal waves.

Potential flow theory, so viscous effects are neglected.

Viscous roll damping will be added by empirical formulas.

Substantial disagreements can be found between calculated and experimental data of wave loads at low frequencies of encounter in following waves. In practice, these "near-zero frequency of encounter" problems are solved by forcing the wave loads to go to zero, artificially.

For high-speed vessels, unsteady divergent wave systems became important. This effect is neglected.

All waves generated by the ship are propagating in directions perpendicular to the center plane of the ship.

Interactions between cross sections are neglected.

Strip theory is based upon linearity, the ship motions are supposed to be small, relative to the cross sectional dimensions of the ship.

Only hydrodynamic effects of the hull below the still water level are accounted for.

The strip theory does not distinguish between various above water hull forms.

Added resistance of a ship due to waves is proportional to the vertical relative motions squared; its inaccuracy will be gained strongly by these motions.

Authors such as Journee, Bunnik and Van Daleen agree that strip theory methods are able to get relatively accurate predictions for long and slender bodies but they disagree on the length to breadth ratio L/B . The first states that $L/B \geq 3$ and the two last mention that L/B ratio over 5.

Strip theories are used for engineering purposes, since they provide robust and quite accurate results in low to moderate sea states. (25th Committee)⁶

4.2.2 Panel Methods

During the 80's and beginning of the 90's Panel Methods were developed to overcome geometry restrictions of the strip theory programs.

Panel methods divide the surface of the ship and the surrounding water into discrete elements (panels). On each of these elements, a distribution of sources and sinks is defined which fulfill the Laplace equation.

Green's theorem gives system of equations for singularity strength on each panel in terms of boundary conditions. Panel methods attempt to solve the Laplace equation in the fluid domain by distribution sources and dipoles on the body and, in some methods, on the free surface. These surface are divided into panels, each one associated with a source and dipole distribution of unknown strength.

Green's theorem relates the source and dipole distribution strength to the potential and normal velocity on each panel. The boundary conditions to be applied to the problem are often linearized and they determine either the potential or the normal velocity on each panel.

Having solved for the unknown source and dipole strengths, Green's theorem may be used to find the potential at any point in the fluid domain. Hydrodynamic forces are found from pressure integration and are used with Newton's Law to determine motions.

⁶(25th Committee)

4.2.2.1 Rankine Panel Method

The Rankine Panel methods distribute panels on both the body and the free surface. Although with Rankine methods there is a greater freedom in applying the free surface boundary conditions, it comes with a cost. This cost is the introduction of extra errors due to discretization of the free surface.

4.2.2.2 Raised Panel Method

The Raised Panel Method is used to implement the body-exact iterative linearization about a basis wave flow. Such method places singularity distributions at a distance above the $z=0$ plane, with the collocation points still on the free surface.

The clear benefit of this method is that the free surface panels do not have to be re-created at each iteration, and the free surface to body influence coefficients need only be calculated once. The method also has nice numerical properties since the infinite velocities which are self-induced on each free surface panel are no longer in the fluid domain. In addition, the process of linearizing the flow about the previous solution is made more straightforward since the flow field at the last iteration is always defined at the next estimation of the position of the free surface. So briefly:

- No free surface discretization necessary at each iteration
- Influence coefficients of free surface panels to body collocations points calculated only once
- Due to distance, h (distance between the free surface and the $z=0$ plane), the velocity field induced in the fluid domain from each panel is smoother.

4.3 Domain of Calculations

Time domain and frequency domain are two different approaches to the same dynamic system. They are interchangeable hence, there is no loss of information when changing from domain to domain. So, they are complementary points of view that lead to a complete, clear understanding of the behavior of a dynamic engineering system. In the time domain we measure how long something takes, whereas in the frequency domain we measure how fast or slow it is.

4.3.1 Frequency Domain

The frequency domain allows us to determine the ship reaction to harmonic waves of different wavelength and wave directions. The disadvantages of the studies in the frequency domain is their restriction to harmonic waves and their inability to use real time wave elevations for the calculation of motion responses.

4.3.2 Time Domain

With time domain we can compute the forces on the ship for given motions at one point in time and so, based on that information, we can compute motions at following point in time.

In time domain we can also handle non-harmonic waves and it is not necessary to implement the conditions dependent on every frequency explicitly. (L.Siervigal)⁷

Ship motion analysis in the time domain has significantly increased, replacing frequency domain analysis. Due, mainly, to the trend of building very large ships, there are strong demands for studies related to nonlinear motions and structural loads, and nonlinear analysis in the time domain are essential for such studies. Typical problems include nonlinear wave excitation, the resultant motion, structural loads, green water, slamming and whipping, hydro-elasticity (such as springing), sloshing and coupling with ship motions. Furthermore, it is obvious that the application of a time domain approach is getting more popular, and more sophisticated and direct techniques will be introduced in the future.

⁷(L.Siervigal)

4.4 Semi-Empirical Methods

By definition empirical methods are purely based on experimental data and not on first or theoretical principles. The methods that study the added resistance are not pure theoretical nor purely empirical hence semi-empirical. Those methods are basically based on theory and correlated with experimental data. The robustness of those methods is the prime advantage over others.

Because is not within the scope of the thesis we will mention some of the methods but nevertheless we will get into detail. So, the most intuitive methods of them are based on Beaufort number and often combined with the influence of wind and waves. (Rob Grin) And also methods that predict the speed loss without estimating the added resistance. Also, most of the methods focus either on ship motion induced added resistance or on added resistance due to wave reflection. For the third we can refer to Jinkine and Ferdinande (1974) and for the last to Fujii and Takahashi (1975). For instance Jinkine is fully empirical and provides the wave added resistance in regular head seas. Fujii developed a prediction method for wave reflection at blunt bow shapes and is semi-empirical. It estimates the wave added resistance in regular head seas and seas from the bow quarter. In case you are interested it is recommended to read Rob Grin "On the prediction of added resistance with empirical methods" and also, Jinkine, V and V. Ferdinande " A method for predicting the Added Resistance of Fast Cargo Ships in Head Waves" 1974.

4.5 Experimental techniques

For experimental techniques we understand model basin test. The model experiments can be carried out in calm-water and in waves both regular and irregular. The obvious advantage of performing those model test in model basins is the ability to control the environmental conditions e.g. waves, wind and temperature. The limitations are the dimension of the model due to the dimension of the facility.

The two different methods of measuring added resistance are commonly used in towing tanks are:

- The Semi-Captive test.
 - The Constant Velocity Method
 - The Constant Thrust Method
- The Free Sailing Test.

4.5.1 Semi-Captive Test

In the constant-velocity method, the model is not fully restrained but free to heave and pitch and sometimes free to roll. That means that the yaw, surge and sway motions are restrained. It does not allow any carriage-model speed variation. The standard procedure is to tow the model at constant speed and by means of a dynamometer measure the resistance. Because that procedure, the added resistance can not be measured directly, instead this method requires to run a case in waves and a case in calm water in order to deduct the wave case results off the calm water case at the same speed. The added resistance is then the Froude scale difference between the total resistance in waves and the calm water resistance. The measurements require a 200 wave encounter in beam to head seas and around 30 minutes full scale time in following and stern quartering seas. (Grin)⁸ In head and following seas this test can be done without any issue, however in the rest of cases some practical problems are induced. The connections to the model is also an issue in this case, that is why attention must be paid to avoid influences of the connection on the ship motions and the weight distribution.

In the constant-thrust method, the model is towed by a constant weight, and the resultant speed of the model is measured. The measurement is accomplished, in most cases, by attaching the model to a sub-carriage that can move relative to the main carriage. The towing force is applied to the sub-carriage. The model is free to heave, pitch and surge. It is usually restricted against yaw, roll and sway.

4.5.2 Free Sailing Test

The free sailing test is performed with a complete free-sailing model. During theses test the model is self-propelled and connections between model and carriage consist

⁸(Grin)

only of free-hanging thin electric cables for relay of measurement signals and power supply. The model is kept on course by an autopilot reacting on course deviation and rate of turn. With this setup it is not possible to measure resistance and in place thrust, torque and propeller revolutions are measured in calm-water and in waves.

The advantages of the free sailing test against semi-captive are numerous, such as:

- Six(6) DOF(Degrees of Freedom) of motion.
- Minimal influence on the motions by the cables.
- No restriction on waves direction.
- Since thrust is the magnitude measured during tests, it is possible to take into account wake fraction and thrust deduction changes.

The inconvenience is that the drift angle in oblique seas and second order speed variations are also included in the measurements. Even though the latter two effects also occur at full scale, discrepancies can arise if there are no representative diesel engine characteristics and autopilot settings.

It is virtually impossibility to perform a calm-water run and a run in waves at the very same mean speed since there will be always a slightly small speed variation. Thus, it is not possible to directly subtract the mean value of the total thrust in waves and the calm-water thrust. This circumstance is solved by performing multiple runs in calm-water for the applicable speed range and interpolating between the thrust required in calm-water. The result is the added thrust at equal speed as the run in waves. (Grin)⁹.

4.5.3 Uncertainty on Added Resistance experiments

If you never wondered how accurate and reliable the model test results are, we did, and we considered worth to be include in the thesis. Although, we are not going to elaborate on uncertainty for the sake of the extension of the thesis we are including a brief explanation and an example that can yields an understanding on the relative reliability of the added resistance results in model basins.

In any experiment there is an uncertainty, and a model test in a towing tank is not an exception. Rob Grin from MARIN in the Netherlands, had written on this topic and gave an example. So, following his lead and explanation we will say that wave added resistance and thrust measurements have a relatively high uncertainty, in particular when test are preformed in typical service conditions where the speed is high and the waves are low. This is because in these conditions the added resistance is an order of magnitude smaller than the calm-water resistance and total resistance in waves. Although the latter two have generally small uncertainty, this uncertainty has the same order of magnitude as the resulting wave added resistance. This is illustrated in the example given by Grin, where the uncertainty in the resistance measurements

⁹(Grin)

is assumed to be $\pm 2\%$ (95% confidence interval).

When the measured total is 1500 ± 30 kN and the measured calm-water resistance is 1400 ± 28 kN, then the added resistance is 100 ± 41 kN ($\pm 41\%$). When sailing at low speed and high waves the uncertainty is considerably smaller. For instance when the measured total resistance is 1200 ± 24 kN and the calm-water resistance is 600 ± 12 kN then the added resistance is 600 ± 27 kN ($\pm 4.5\%$).

The aim of test in regular waves is to obtain the transfer functions, which in the case of added thrust is obtained by dividing the mean wave added thrust by the wave amplitude squared (ζ_a^2). The wave amplitude is obtained by harmonic analysis. This increases the uncertainty further as the wave amplitude sometimes contains instabilities and is low in case of short waves (see also Bingjie and Steen, 2010). (Grin)¹⁰.

In a experimental set up model test we can face the following uncertainties that we are not going to elaborate since they are almost self explanatory. (Dong-Min Park)¹¹:

- Basic instrument uncertainty
- Mass distribution uncertainty
- Calibration Uncertainty
- Geometry Uncertainty
- Measurement Uncertainty
- Uncertainty Analysis of Waves
- Uncertainty Analysis of Heave
- Uncertainty Analysis of Pitch

¹⁰(Grin)

¹¹(Dong-Min Park)

5.1 Conclusions Chapter 1 - Resistance of a Ship in a Seaway

From that chapter we can extract the following conclusions:

Since the vessel's performance underway and her ability to sustain a defined speed are the two main aspects for a successful ship design. The effort must be done to make accurate predictions of those two aspects.

Since the motion prediction is in great interest when designing a vessel, attention must be paid on that matter.

Previous solution approaches for the weather margin are nowadays not effective nor efficient, and so that procedure must be avoided when designing a vessel.

Although, the results of analytical methods, which are based on known ship motions, tend to not completely agree with experiment data. Those methods provide adequate guidelines for the designer to estimate the power requirements in a seaway.

5.2 Conclusions Chapter 2 - Added Resistance in Waves

The conclusions from this chapter are:

The added resistance in waves is an extra-induced energy loss.

The added resistance in waves can be considered a non-viscous phenomenon.

The added resistance can be scaled from model to ship by multiplying the scale factor by the cube power.

The drift force has the largest contribution followed by the damping forces and finally the diffraction effects.

The motion induced added resistance is due to the radiated waves (due to ship motions). Their largest contributors are the heave and pitch motions.

The roll effects in the added resistance is neglected due to its small magnitude compared to heave and pitch motions effects.

The ratio L_{pp}/λ is an important parameter for the added resistance phenomenon.

In waves of short wavelength, the hull motion is small, and the resistance is mainly due to the diffraction of waves. When the wavelength increases, the added resistance due to motions becomes dominant.

The most dominant component that induces the added resistance are the vertical motions.

Ship motions and forces in irregular waves can be expressed as the sum of the responses in regular waves.

The application of the linear theory has the limitation of the wave steepness.

The added resistance in regular waves varies linearly with the wave height squared at a constant wave height.

The second order characteristic of the added resistance makes it hard to obtain accurate predictions.

The added resistance is very sensitive to motion prediction. Therefore, is more important an accurate prediction of the vertical motions than developing a more sophisticated added resistance theory.

Although the added resistance is a second order problem, the linear wave velocity potential is the only one required.

It is possible to express the added resistance in irregular waves using the superposition technique. However, the ship response to regular waves do not indicate directly the behavior in irregular waves.

The common added resistance in waves used for design purposes is the mean added resistance.

The added resistance in waves is independent from the calm-water resistance.

5.3 Conclusions Chapter 3 - Predicting the Added Resistance

The added resistance can be studied from several points of view.

The principles to predict the added resistance can be applied in different formulations for the very same problem.

The actual trend is to predict the added resistance by numerical applications and in those applications, the trend is to move from the frequency domain to time domain, from strip theory type to full 3-D schemes, from linear to non-linear problems and from potential-flow to viscous flow computations.

From the Havelock theory, we can extract the following conclusions:

Havelock's proposal is an approximation since it neglects the diffraction effects. However, it provides valuable insights into the added resistance.

Both the motion amplitudes and their phases are important factors when calculating the added resistance.

The maximum added resistance will likely occur in the region of pitch and heave resonance.

A vessel with poor motion characteristics will have less added resistance due to the direct pitch and heave motion relationship.

From Maruo's theory:

Maruo's neglects the effects in the variation of the ship speed due to the fact that pitch and heave motion of the ship dominates the effects of surge.

From Joosen's theory:

The wave diffraction effect can be neglected (except for very small waves where it becomes dominant) due to the fact that the drift force in the longitudinal direction in head seas depends solely on the radiated wave potential.

Although not as accurate as Gerritsma and Beukelman the Joosen's method is ease in terms of implementation.

From Gerritsma and Beukelman's method:

It is more accurate due to the more accurate handling of diffraction effects and cross coupling method.

This method is more complicated to implement since it requires an accurate knowledge of the distribution of the sectional added mass and damping.

From Boese's method:

Boese's method introduced a more elaborated initial motion data consideration.

The use of a transverse strip may therefore result in a poor problem formulation, and it is possible that a completely different approach is required for added drag theory.

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